PATENT APPLICATION

OF

SANJAY CHATURVEDI
ANNE MAE GAFFNEY
RUOZHI SONG

and

ELSIE MAE VICKERY

FOR

MIXED METAL OXIDE CATALYST

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MIXED METAL OXIDE CATALYST

The present invention relates to an improved catalyst for the oxidation of alkanes or a mixture of alkanes and alkenes to their corresponding unsaturated carboxylic acids by vapor phase catalytic partial oxidation; to a method of making the catalyst; and to a process for the vapor phase catalytic partial oxidation of alkanes or a mixture of alkanes and alkenes to their corresponding unsaturated carboxylic acids.

The present invention also relates to a method of producing unsaturated nitriles by subjecting alkanes or a mixture of alkanes and alkenes to vapor phase catalytic partial oxidation in the presence of ammonia.

Nitriles, such as acrylonitrile and methacrylonitrile, have been industrially produced as important intermediates for the preparation of fibers, synthetic resins, synthetic rubbers, and the like. The most popular method for producing such nitriles is to subject an olefin such as propene or isobutene to a catalytic reaction with ammonia and oxygen in the presence of a catalyst in a gaseous phase at a high temperature. Known catalysts for conducting this reaction include a Mo-Bi-P-O catalyst, a V-Sb-O catalyst, a Sb-U-V-Ni-O catalyst, a Sb-Sn-O catalyst, a V-Sb-W-P-O catalyst and a catalyst obtained by mechanically mixing a V-Sb-W-O oxide and a Bi-Ce-Mo-W-O oxide. However, in view of the price difference between propane and propene or between isobutane and isobutene, attention has been drawn to the development of a method for producing acrylonitrile or methacrylonitrile by an ammoxidation reaction wherein a lower alkane, such as propane or isobutane, is used as a starting material, and it is catalytically reacted with ammonia and oxygen in a gaseous phase in the presence of a catalyst.

In particular, U.S. Patent No. 5,281,745 discloses a method for producing an unsaturated nitrile comprising subjecting an alkane and ammonia in the gaseous state to catalytic oxidation in the presence of a catalyst which satisfies the conditions:

(1) the mixed metal oxide catalyst is represented by the empirical formula

$$Mo_aV_bTe_cX_xO_n$$

wherein X is at least one element selected from the group consisting of niobium, tantalum, tungsten, titanium, aluminum, zirconium, chromium, manganese, iron, ruthenium, cobalt, rhodium, nickel, palladium, platinum, antimony, bismuth, boron and cerium and, when a = 1, b = 0.01 to 1.0, c = 0.01 to 1.0, x = 0.01 to 1.0 and n is a number such that the total valency of the metal elements is satisfied; and

(2) the catalyst has X-ray diffraction peaks at the following angles (±0.3°) of 2θ in its X-ray diffraction pattern: 22.1°, 28.2°, 36.2°, 45.2° and 50.0°.

Similarly, Japanese Laid-Open Patent Application Publication No. 6-228073 discloses a method of nitrile preparation comprising reacting an alkane in a gas phase contact reaction with ammonia in the presence of a mixed metal oxide catalyst of the formula

$$W_aV_bTe_cX_xO_n$$

wherein X represents one or more elements selected from niobium, tantalum, titanium, aluminum, zirconium, chromium, manganese, iron, ruthenium, cobalt, rhodium, nickel, palladium, platinum, antimony, bismuth, indium and cerium and, when a = 1, b = 0.01 to 1.0, c = 0.01 to 1.0, x = 0.01 to 1.0 and n is determined by the oxide form of the elements.

U.S. Patent No. 6,043,185 also discloses a catalyst useful in the manufacture of acrylonitrile or methacrylonitrile by the catalytic reaction in the vapor phase of a paraffin selected from propane and isobutane with molecular oxygen and ammonia by catalytic contact of the reactants in a reaction zone with a catalyst, wherein the catalyst has the empirical formula

$$Mo_aV_bSb_cGa_dX_eO_x$$

where X is one or more of As, Te, Se, Nb, Ta, W, Ti, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pd, Pt, B, In, Ce, Re, Ir, Ge, Sn, Bi, Y, Pr, an alkali metal and an alkaline earth metal; and when a = 1, b = 0.0 to 0.99, c = 0.01 to 0.9, d = 0.01 to 0.5, e = 0.0 to 1.0 and x is determined by the oxidation state of the cations present.

Unsaturated carboxylic acids such as acrylic acid and methacrylic acid are industrially important as starting materials for various synthetic resins, coating materials and plasticizers. Commercially, the current process for acrylic acid manufacture involves a two-step catalytic oxidation reaction starting with a propene feed. In the first stage, propene is converted to acrolein over a modified bismuth molybdate catalyst. In the second stage, acrolein product from the first stage is converted to acrylic acid using a catalyst composed of mainly molybdenum and vanadium oxides. In most cases, the catalyst formulations are proprietary to the catalyst supplier, but, the technology is well established. Moreover, there is an incentive to develop a single step process to prepare the unsaturated acid from its corresponding alkene. Therefore, the prior art describes cases where complex metal oxide catalysts are utilized for the preparation of unsaturated acid from a corresponding alkene in a single step.

European Published Patent Application No. 0 630 879 B1 discloses a process for producing an unsaturated aldehyde and a carboxylic acid which comprises subjecting

propene, isobutene or tertiary butanol to gas phase catalytic oxidation with molecular oxygen in the presence of (i) a catalyst composite oxide represented by the formula

$$Mo_aBi_bFe_cA_dB_eC_fD_gO_x$$

wherein A represents Ni and/or Co, B represents at least one element selected from Mn, Zn, Ca, Mg, Sn and Pb, C represents at least one element selected from P, B, As, Te, W, Sb and Si, and D represents at least one element selected from K, Rb, Cs and Tl; and wherein, when $a = 12$, $0 < b \leq 10$, $0 < c \leq 10$, $1 \leq d \leq 10$, $0 \leq e \leq 10$, $0 \leq f \leq 20$ and $0 \leq g \leq 2$, and x has a value dependent on the oxidation state of the other elements; and (ii) a molybdenum oxide which in itself is substantially inert to said gas phase catalytic oxidation to provide the corresponding unsaturated aldehyde and unsaturated carboxylic acid.

Japanese Laid-Open Patent Application Publication No. 07-053448 discloses the manufacture of acrylic acid by the gas-phase catalytic oxidation of propene in the presence of mixed metal oxides containing Mo, V, Te, O and X wherein X is at least one of Nb, Ta, W, Ti, Al, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pd, Pt, Sb, Bi, B, In, Li, Na, K, Rb, Cs and Ce.

Published International Application No. WO 00/09260 discloses a catalyst for selective oxidation of propene to acrylic acid and acrolein containing a catalyst composition comprising the elements Mo, V, La, Pd, Nb and X in the following ratio:

$$Mo_aV_bLa_cPd_dNb_eX_f$$

wherein X is Cu or Cr or a mixture thereof,

a is 1,

b is 0.01 to 0.9,

c is >0 to 0.2

d is 0.0000001 to 0.2,

e is 0 to 0.2, and

f is 0 to 0.2; and

wherein the numerical values of a, b, c, d, e and f represent the relative gram-atom ratios of the elements Mo, V, La, Pd, Nb and X, respectively, in the catalyst and the elements are present in combination with oxygen.

Commercial incentives also exist for producing acrylic acid using a lower cost propane feed. Therefore, the prior art describes cases wherein a mixed metal oxide catalyst is used to convert propane to acrylic acid in one step.

U.S. Patent No. 5,380,933 discloses a method for producing an unsaturated carboxylic acid comprising subjecting an alkane to a vapor phase catalytic oxidation reaction in the

presence of a catalyst containing a mixed metal oxide comprising, as essential components, Mo, V, Te, O and X, wherein X is at least one element selected from the group consisting of niobium, tantalum, tungsten, titanium, aluminum, zirconium, chromium, manganese, iron, ruthenium, cobalt, rhodium, nickel, palladium, platinum, antimony, bismuth, boron, indium and cerium; and wherein the proportions of the respective essential components, based on the total amount of the essential components, exclusive of oxygen, satisfy the following relationships:

$0.25 < r(Mo) < 0.98$, $0.003 < r(V) < 0.5$, $0.003 < r(Te) < 0.5$ and $0.003 < r(X) < 0.5$, wherein r(Mo), r(V), r(Te) and r(X) are the molar fractions of Mo, V, Te and X, respectively, based on the total amount of the essential components exclusive of oxygen. See also, European Application No. EP 0962253.

Published International Application No. WO 00/29106 discloses a catalyst for selective oxidation of propane to oxygenated products including acrylic acid, acrolein and acetic acid, said catalyst system containing a catalyst composition comprising

$$Mo_aV_bGa_cPd_dNb_eX_f$$

wherein X is at least one element selected from La, Te, Ge, Zn, Si, In and W,

a is 1,

b is 0.01 to 0.9,

c is >0 to 0.2,

d is 0.0000001 to 0.2,

e is >0 to 0.2, and

f is .0 to 0.5; and

wherein the numerical values of a, b, c, d, e and f represent the relative gram-atom ratios of the elements Mo, V, Ga, Pd, Nb and X, respectively, in the catalyst and the elements are present in combination with oxygen.

Japanese Laid-Open Patent Application Publication No. 2000-037623 discloses a method for producing an unsaturated carboxylic acid comprising subjecting an alkane to a vapor phase catalytic oxidation in the presence of a catalyst having the empirical formula

$$MoV_aNb_bX_cZ_dO_n$$

wherein X is at least one element selected from the group consisting of Te and Sb, Z is at least one element selected from the group consisting of W, Cr, Ta, Ti, Zr, Hf, Mn, Re, Fe, Ru, Co, Rh, Ni, Pd, Pt, Ag, Zn, B, Al, Ga, In, Ge, Sn, Pb, P, Bi, Y, rare earth elements and

alkaline earth elements, $0.1 \leq a \leq 1.0$, $0.01 \leq b \leq 1.0$, $0.01 \leq c \leq 1.0$, $0 \leq d \leq 1.0$ and n is determined by the oxidation states of the other elements.

One example of the use of a deposition technique to form a catalyst is given in WO 99/53557, where Pt-Mo alloys are deposited on carbon supports to be used as anodic catalysts.

Despite the above-noted attempts to provide new and improved catalysts for the oxidation of alkanes to unsaturated carboxylic acids and for the ammoxidation of alkanes to unsaturated nitriles, one impediment to the provision of a commercially viable process for such catalytic oxidations is the identification of a catalyst providing adequate conversion and suitable selectivity, thereby providing sufficient yield of the unsaturated product.

By the present invention, there are provided catalysts wherein the performance is enhanced by doping catalysts comprising a mixed metal oxide with a metal or a combination of metals.

Thus, in a first aspect, the present invention provides a process for improving the performance characteristics of a catalyst, the process comprising: providing a catalyst comprising a mixed metal oxide having the empirical formula

$$A_aD_bE_cX_dO_e$$

wherein A is at least one element selected from the group consisting of Mo and W, D is at least one element selected from the group consisting of V and Ce, E is at least one element selected from the group consisting of Te, Sb and Se, and more preferably from the group consisting of Te and Sb, and X is at least one element selected from the group consisting of Nb, Ta, Ti, Al, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pt, Sb, Bi, B, In, As, Ge, Sn, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Ra, Hf, Pb, P, Pm, Eu, Gd, Dy, Ho, Er, Tm, Yb and Lu; and a = 1, b = 0.01 to 1.0, c = 0.01 to 1.0, d = 0.01 to 1.0, and e is dependent on the oxidation state of the other elements; and vapor depositing onto said catalyst at least one dopant metal for improving catalytic performance.

In a second aspect, the present invention provides a process for producing an unsaturated carboxylic acid, which comprises subjecting an alkane or a mixture of an alkane and an alkene to a vapor phase catalytic partial oxidation reaction in the presence of a catalyst produced by the process of the first aspect of this invention.

In a third aspect, the present invention provides a process for producing an unsaturated nitrile, which comprises subjecting an alkane, or a mixture of an alkane and an alkene, and

ammonia to a vapor phase catalytic partial oxidation reaction in the presence of a catalyst produced by the process of the first aspect of this invention.

In a fourth aspect of the present invention, the present invention provides a process for preparing a catalyst, comprising:

a) vapor depositing, one upon the other, a plurality of thin films, each thin film containing at least one of the elements A, D, E and X to form a composite of A, D, E and X, wherein A is at least one element selected from the group consisting of Mo and W, D is at least one element selected from the group consisting of V and Ce, E is at least one element selected from the group consisting of Te, Sb and Se, and X is at least one element selected from the group consisting of Nb, Ta, Ti, Al, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pt, Sb, Bi, B, In, As, Ge, Sn, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Ra, Hf, Ag, Pb, P, Pm, Eu, Gd, Dy, Ho, Er, Tm, Yb and Lu; and

b) calcining said plurality of thin films to form a catalyst comprising a mixed metal oxide having a base composition empirical formula $A_aD_bE_cX_dO_e$ wherein A, D, E and X are as previously defined, O is oxygen and, when a = 1, b = 0.01 to 1.0, c = 0.01 to 1.0, d = 0.01 to1.0, and e is dependent on the oxidation state of said other elements.

In a fifth aspect, the present invention provides a process for preparing a catalyst, comprising:

vapor depositing, one upon the other, a plurality of thin films, each thin film containing at least one of the elements Mo, V, Nb and X, to form a composite of Mo, V, Nb and X, where X is at least one element selected from the group consisting of Ta, Ti, Al, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pt, B, In, Ce, As, Ge, Sn, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Hf, Pb, P, Pm, Eu, Gd, Dy, Ho, Er, Tm, Yb, Lu, Au, Ag, Re, Pr, Zn, Ga, Pd, Ir, Nd, Y, Sm, Tb, Cu and Sc; and

calcining said composite to form a catalyst. .

In a sixth aspect, the present invention provides a process for preparing a catalyst, comprising the steps of:

vapor depositing, one upon the other, a plurality of thin films, each thin film containing at least one of the elements Mo, V, Te and X^1, to form a composite of Mo, V, Te and X^1, where X^1 is at least one element selected from the group consisting of Sc, Y, La, Re, Ir, Cu, Ag, Au, Zn, Ga, Si, Ge, As, Pb, S, Se, Sn and Bi; and

calcining said composite to form a catalyst.

The preferred mixed metal oxide exhibits the following five main diffraction peaks at specific diffraction angles (2θ) in the X-ray diffraction pattern of the treated mixed metal oxide (as measured using Cu-Kα radiation as the source):

Diffraction angle 2θ (±0.3°)	X-ray lattice plane Spacing medium (Å)	Relative intensity
22.1°	4.02	100
28.2°	3.16	20~150
36.2°	2.48	5~60
45.2°	2.00	2~40
50.0°	1.82	2~40

The intensity of the X-ray diffraction peaks may vary upon the measuring of each crystal. However, the intensity, relative to the peak intensity at 22.1° being 100, is usually within the above ranges. Generally, the peak intensities at 2θ = 22.1° and 28.2° are distinctly observed. However, so long as the above five diffraction peaks are observable, the basic crystal structure is the same even if other peaks are observed in addition to the five diffraction peaks, and such a structure is useful for the present invention.

Turning now in more specific detail to the first aspect of the present invention, the improved catalyst is prepared by introducing a metal dopant into a catalyst, by deposition. As discussed herein, the step of deposition is accomplished by employment of a deposition technique selected from chemical vapor deposition or physical deposition. The skilled artisan will appreciate the many conventionally employed approaches to chemical vapor deposition, e.g., at atmospheric pressure or low pressure, employing a laser, plasma assisted, chemical vapor infiltration, photochemical vapor deposition, metal-organic chemical vapor deposition, chemical beam epitaxy, or the like. Likewise, the skilled artisan will recognize as among the techniques for physical vapor deposition, the employment of sputtering, molecular beam epitaxy, vacuum evaporation techniques or the like. Other suitable deposition techniques may likewise be employed including, for example, spray coating, plating, electrochemical deposition or the like.

It should be appreciated that pursuant to the preferred aspects of the present invention that are discussed herein, a catalyst or catalyst precursor is doped after it is prepared. However, also within the scope of the present invention, it is contemplated that the entirety of

the catalyst or catalyst precursor is prepared with or without a suitable dopant, and is deposited onto a suitable support by chemical deposition, physical deposition or another deposition technique. This might be done by mixing the ingredients prior to deposition or during deposition. It might also be accomplished by building a plurality of layers of the same or different composition through the use of deposition techniques.

A particularly preferred approach to the preparation of catalysts in accordance with the present invention involves the preparation of a catalyst or catalyst precursor, followed by the doping with a preferred dopant, through deposition in accordance with the present invention, and more preferably through the use of sputtering, which will be illustrated in further detail herein.

Preferably, when employed, the dopant is selected from the group consisting of Pd, Au, Pd-Au alloys, Ga, Cu, Ag, Ni, Zn, Pr, Re, Ir, Nd, Y, Sm, Tb, In, Bi and Se or mixtures thereof. In a particularly preferred embodiment the dopant is selected from the group consisting of Pd, Pd-Au alloys and mixtures thereof. A particularly preferred Pd-Au alloy includes gold and palladium in a ratio of 1:5 to 5:1 and more preferably 1:1.

In a first step, a catalyst precursor admixture may be formed by admixing metal compounds, preferably at least one of which contains oxygen, and at least one solvent, in appropriate amounts to form the admixture, which may be a slurry, solution or combination thereof. Liquids are then removed, and the precursor admixture calcined.

More specifically, as mentioned, though a slurry may be formed, preferably, a precursor solution is instead formed at this stage of the catalyst preparation. Generally, the metal compounds in the solution will contain elements A, D, E, X, and O, as previously defined.

Suitable solvents for the precursor solution include water; alcohols including, but not limited to, methanol, ethanol, propanol, and diols, etc.; as well as other polar solvents known in the art. Generally, water is preferred. The water is any water suitable for use in chemical syntheses including, without limitation, distilled water and de-ionized water. The amount of water present is preferably an amount sufficient to keep the elements substantially in solution long enough to avoid or minimize compositional and/or phase segregation during the preparation steps. Accordingly, the amount of water will vary according to the amounts and solubilities of the materials combined. Preferably, though lower concentrations of water are possible for forming a slurry, as stated above, the amount of water is sufficient to ensure an aqueous solution is formed, at the time of mixing.

By way of example, when a mixed metal oxide of the formula $Mo_aV_bTe_cNb_dO_e$ (wherein the element A is Mo, the element D is V, the element E is Te and the element X is Nb) is to be prepared, an aqueous solution of niobium oxalate and an aqueous solution or slurry of ammonium heptamolybdate, ammonium metavanadate and telluric acid are admixed so that the atomic ratio of the respective metal elements would be in the prescribed proportions.

Once the resulting treated admixture is formed, the liquid therein is removed by any suitable method, known in the art, for forming a catalyst precursor. Such methods include, without limitation, vacuum drying, freeze drying, spray drying, rotary evaporation and air-drying. Vacuum drying is generally performed at pressures ranging from 10 mm Hg to 500 mm Hg. Freeze drying typically entails freezing the slurry or solution, using , for instance, liquid nitrogen, and drying the frozen slurry or solution under vacuum. Spray drying is generally performed under an inert atmosphere such as nitrogen or argon, with an inlet temperature ranging from 125°C to 200°C and an outlet temperature ranging from 75°C to 150°C. Rotary evaporation is generally performed at a bath temperature of from 25°C to 90°C and at a pressure of from 10 mm Hg to 760 mm Hg, preferably at a bath temperature of from 40° to 90°C and at a pressure of from 10 mm Hg to 350 mm Hg, more preferably at a bath temperature of from 40°C to 60°C and at a pressure of from 10 mm Hg to 40 mm Hg. Air drying may be effected at temperatures ranging from 25°C to 90°C. Rotary evaporation or air-drying are generally preferred.

Once obtained, the resulting catalyst precursor is calcined. The calcination may be conducted in an oxygen-containing atmosphere or in the substantial absence of oxygen, e.g., in an inert atmosphere or in vacuo. The inert atmosphere may be any material which is substantially inert, i.e., does not react or interact with, the catalyst precursor. Suitable examples include, without limitation, nitrogen, argon, xenon, helium or mixtures thereof. Preferably, the inert atmosphere is argon or nitrogen. The inert atmosphere may flow over the surface of the catalyst precursor or may not flow thereover (a static environment). When the inert atmosphere does flow over the surface of the catalyst precursor, the flow rate can vary over a wide range, e.g., at a space velocity of from 1 to 500 hr^{-1}.

The calcination is usually performed at a temperature of from 350°C to 850°C, preferably from 400°C to 700°C, more preferably from 500°C to 640°C. The calcination is performed for an amount of time suitable to form the aforementioned catalyst. Typically, the

calcination is performed for from 0.5 to 30 hours, preferably for from 1 to 25 hours, more preferably for from 1 to 15 hours, to obtain the desired doped mixed metal oxide.

In a preferred mode of operation, the catalyst precursor is calcined in two stages. In the first stage, the catalyst precursor is calcined in an oxidizing environment (e.g. air) at a temperature of from 275°C to 400°C, preferably from 275°C to 325°C for from 15 minutes to 8 hours, preferably for from 1 to 3 hours. In the second stage, the material from the first stage is calcined in a non-oxidizing environment (e.g., an inert atmosphere, such as argon) at a temperature of from 500°C to 700°C, preferably for from 550°C to 650°C, for 15 minutes to 8 hours, preferably for from 1 to 3 hours. Optionally, a reducing gas, such as, for example, ammonia or hydrogen, may be added during the second stage calcination.

In a particularly preferred mode of operation, the catalyst precursor in the first stage is placed in the desired oxidizing atmosphere at room temperature and then raised to the first stage calcination temperature and held there for the desired first stage calcination time. The atmosphere is then replaced with the desired non-oxidizing atmosphere for the second stage calcination, the temperature is raised to the desired second stage calcination temperature and held there for the desired second stage calcination time.

Although any type of heating mechanism, e.g., a furnace, may be utilized during the calcination, it is preferred to conduct the calcination under a flow of the designated gaseous environment. Therefore, it is advantageous to conduct the calcination in a bed with continuous flow of the desired gas(es) through the bed of solid catalyst precursor particles.

With calcination, a catalyst is formed having the formula $A_aD_bE_cX_dO_e$, wherein A, D, E, X, O, a, b, c, d and e are as previously defined.

Though it may be possible to introduce the dopants of the present invention prior to or during calcination, preferably they are introduced after calcination. Introduction takes place by inducing an atomic flux or otherwise finely dividing a dopant source material and contacting the resulting source material with the catalyst. In one highly preferred embodiment, introduction of the dopant to the catalyst is by sputtering, particularly wherein the sputter target includes the above-described dopant. Accordingly, it is contemplated that a bulk quantity (i.e., sufficient for commercial scale reactions) of the catalyst or catalyst precursor admixture is loaded in one or more steps into a chamber of a sputter coater. The sputter coater will also include a sputter target including the dopant. The chamber preferably is evacuated and then filled to a suitable pressure (e.g. 50 to 300 millitorr) with a suitable working gas (e.g., an inert gas such as argon). A suitable stimulus is applied for a sufficient

time to form a plasma or otherwise accelerate the resulting charged gas ions into the oppositely biased sputter target. For instance, the stimulus might be current (e.g., 10 to 80 milliamps). The time of sputtering may range from a few seconds upward to a few minutes (e.g., at least 10 seconds and more preferably about 20 seconds to about 120 seconds per each 6 to 10 grams of catalyst or catalyst precursor admixture). This procedure optionally is repeated until the desired amount or performance of catalyst is achieved.

The starting materials for the above doped mixed metal oxide are not limited to those described above. A wide range of materials including, for example, oxides, nitrates, halides or oxyhalides, alkoxides, acetylacetonates, and organometallic compounds may be used. For example, ammonium heptamolybdate may be utilized for the source of molybdenum in the catalyst. However, compounds such as MoO_3, MoO_2, $MoCl_5$, $MoOCl_4$, $Mo(OC_2H_5)_5$, molybdenum acetylacetonate, phosphomolybdic acid and silicomolybdic acid may also be utilized instead of ammonium heptamolybdate. Similarly, ammonium metavanadate may be utilized for the source of vanadium in the catalyst. However, compounds such as V_2O_5, V_2O_3, $VOCl_3$, VCl_4, $VO(OC_2H_5)_3$, vanadium acetylacetonate and vanadyl acetylacetonate may also be utilized instead of ammonium metavanadate. The tellurium source may include telluric acid, $TeCl_4$, $Te(OC_2H_5)_5$, $Te(OCH(CH_3)_2)_4$ and TeO_2. The niobium source may include ammonium niobium oxalate, Nb_2O_5, $NbCl_5$, niobic acid or $Nb(OC_2H_5)_5$ as well as the more conventional niobium oxalate.

As discussed, without limitation, examples of preferred treatment sources include palladium or gold-palladium alloys, which are provided as sputter targets. A preferred gold-palladium alloy includes gold and palladium in a ratio of 1:5 to 5:1 and more preferably 1:1. Other metals may be employed, such as Ga, Cu, Ag, Ni, Zn, Pr, Re, Ir, Nd, Y, Sm, Tb, In, Bi and Se or mixtures thereof provided that the metals can be provided as a sputter target.

The doped mixed metal oxide, thus obtained, exhibits excellent catalytic activities by itself. However, the mixed metal oxide can be converted to a catalyst having higher activities by grinding before, during or after sputtering. There is no particular restriction as to the grinding method, and conventional methods may be employed. As a dry grinding method, a method of using a gas stream grinder may, for example, be mentioned wherein coarse particles are permitted to collide with one another in a high-speed gas stream for grinding. The grinding may be conducted not only mechanically but also by using a mortar or the like in the case of a small-scale operation.

As a wet grinding method wherein grinding is conducted in a wet state by adding water or an organic solvent to the above mixed metal oxide, a conventional method of using a rotary cylinder-type medium mill or a medium-stirring type mill, may be mentioned. The rotary cylinder-type medium mill is a wet mill of the type wherein a container for the object to be ground is rotated, and it includes, for example, a ball mill and a rod mill. The medium-stirring type mill is a wet mill of the type wherein the object to be ground, contained in a container is stirred by a stirring apparatus, and it includes, for example, a rotary screw type mill, and a rotary disc type mill.

The conditions for grinding may suitably be set to meet the nature of the above-mentioned doped mixed metal oxide, the viscosity, the concentration, etc. of the solvent used in the case of wet grinding, or the optimum conditions of the grinding apparatus. However, it is preferred that grinding is conducted until the average particle size of the ground catalyst precursor would usually be at most 20μm, more preferably at most 5μm. Improvement in the catalytic performance may occur due to such grinding.

Further, in some cases, it is possible to further improve the catalytic activities by further adding a solvent to the ground catalyst precursor to form a solution or slurry, followed by drying again. There is no particular restriction as to the concentration of the solution or slurry, and it is usual to adjust the solution or slurry so that the total amount of the starting material compounds for the ground catalyst precursor is from 10 to 60 wt %. Then, this solution or slurry is dried by a method such as spray drying, freeze drying, evaporation to dryness or vacuum drying, preferably by the spray drying method. Further, similar drying may be conducted also in the case where wet grinding is conducted.

The oxide obtained by the above-mentioned method may be used as a final catalyst, but it may further be subjected to heat treatment usually at a temperature of from 200° to 700° C for from 0.1 to 10 hours.

The resulting mixed metal oxide may be used by itself as a solid catalyst. It also may be formed into a catalyst with a suitable carrier according to art-disclosed techniques. Further, it may be processed to a suitable shape or particle size using art disclosed techniques, depending upon the scale or system of the reactor.

Turning now in more specific detail to the second aspect of the present invention, the present invention provides a process for producing an unsaturated carboxylic acid, which comprises subjecting an alkane, or a mixture of an alkane and an alkene (“alkane/alkene”), to

a vapor phase catalytic oxidation reaction in the presence of a catalyst containing the above doped mixed metal oxide, to produce an unsaturated carboxylic acid.

In the production of such an unsaturated carboxylic acid, it is preferred to employ a starting material gas that contains steam. In such a case, as a starting material gas to be supplied to the reaction system, a gas mixture comprising a steam-containing alkane, or a steam-containing mixture of alkane and alkene, and an oxygen-containing gas, is usually used. However, the steam-containing alkane, or the steam-containing mixture of alkane and alkene, and the oxygen-containing gas may be alternately supplied to the reaction system. The steam to be employed may be present in the form of steam gas in the reaction system, and the manner of its introduction is not particularly limited.

Further, as a diluting gas, an inert gas such as nitrogen, argon or helium may be supplied. The molar ratio (alkane or mixture of alkane and alkene): (oxygen) : (diluting gas) : (H_2O) in the starting material gas is preferably (1) : (0.1 to 10): (0 to 20) : (0.2 to 70), more preferably (1) : (1 to 5.0) : (0 to 10) : (5 to 40).

When steam is supplied together with the alkane, or the mixture of alkane and alkene, as starting material gas, the selectivity for an unsaturated carboxylic acid is distinctly improved, and the unsaturated carboxylic acid can be obtained from the alkane, or mixture of alkane and alkene, in good yield simply by contacting in one stage. However, the conventional technique utilizes a diluting gas such as nitrogen, argon or helium for the purpose of diluting the starting material. As such a diluting gas, to adjust the space velocity, the oxygen partial pressure and the steam partial pressure, an inert gas such as nitrogen, argon or helium may be used together with the steam.

As the starting material alkane it is preferred to employ a C_{3-8} alkane, particularly propane, isobutane or n-butane; more preferably, propane or isobutane; most preferably, propane. According to the present invention, from such an alkane, an unsaturated carboxylic acid such as an α,β-unsaturated carboxylic acid can be obtained in good yield. For example, when propane or isobutane is used as the starting material alkane, acrylic acid or methacrylic acid will be obtained, respectively, in good yield.

In the present invention, as the starting material mixture of alkane and alkene, it is preferred to employ a mixture of C_{3-8} alkane and C_{3-8} alkene, particularly propane and propene, isobutane and isobutene or n-butane and n-butene. As the starting material mixture of alkane and alkene, propane and propene or isobutane and isobutene are more preferred. Most preferred is a mixture of propane and propene. According to the present invention, from

such a mixture of an alkane and an alkene, an unsaturated carboxylic acid such as an α,β-unsaturated carboxylic acid can be obtained in good yield. For example, when propane and propene or isobutane and isobutene are used as the starting material mixture of alkane and alkene, acrylic acid or methacrylic acid will be obtained, respectively, in good yield. Preferably, in the mixture of alkane and alkene, the alkene is present in an amount of at least 0.5% by weight, more preferably at least 1.0% by weight to 95% by weight; most preferably, 3% by weight to 90% by weight.

As an alternative, an alkanol, such as isobutanol, which will dehydrate under the reaction conditions to form its corresponding alkene, i.e. isobutene, may also be used as a feed to the present process or in conjunction with the previously mentioned feed streams.

The purity of the starting material alkane is not particularly limited, and an alkane containing a lower alkane such as methane or ethane, air or carbon dioxide, as impurities, may be used without any particular problem. Further, the starting material alkane may be a mixture of various alkanes. Similarly, the purity of the starting material mixture of alkane and alkene is not particularly limited, and a mixture of alkane and alkene containing a lower alkene such as ethene, a lower alkane such as methane or ethane, air or carbon dioxide, as impurities, may be used without any particular problem. Further, the starting material mixture of alkane and alkene may be a mixture of various alkanes and alkenes.

There is no limitation on the source of the alkene. It may be purchased, per se, or in admixture with an alkane and/or other impurities. Alternatively, it can be obtained as a by-product of alkane oxidation. Similarly, there is no limitation on the source of the alkane. It may be purchased, per se, or in admixture with an alkene and/or other impurities. Moreover, the alkane, regardless of source, and the alkene, regardless of source, may be blended as desired.

The detailed mechanism of the oxidation reaction of the present invention is not clearly understood, but the oxidation reaction is carried out by oxygen atoms present in the above mixed metal oxide or by molecular oxygen present in the feed gas. To incorporate molecular oxygen into the feed gas, such molecular oxygen may be pure oxygen gas. However, it is usually more economical to use an oxygen-containing gas such as air, since purity is not particularly required.

It is also possible to use only an alkane, or a mixture of alkane and alkene, substantially in the absence of molecular oxygen for the vapor phase catalytic reaction. In such a case, it is preferred to adopt a method wherein a part of the catalyst is appropriately

withdrawn from the reaction zone from time to time, then sent to an oxidation regenerator, regenerated and then returned to the reaction zone for reuse. As the regeneration method of the catalyst, a method may, for example, be mentioned which comprises contacting an oxidative gas such as oxygen, air or nitrogen monoxide with the catalyst in the regenerator usually at a temperature of from 300° to 600°C.

The second aspect of the present invention will be described in still further detail with respect to a case where propane is used as the starting material alkane and air is used as the oxygen source. The reaction system may be preferably a fixed bed system. The proportion of air to be supplied to the reaction system is important for the selectivity for the resulting acrylic acid, and it is usually at most 25 moles, preferably from 0.2 to 18 moles per mole of propane, whereby high selectivity for acrylic acid can be obtained. This reaction can be conducted usually under atmospheric pressure, but may be conducted under a slightly elevated pressure or slightly reduced pressure. With respect to other alkanes such as isobutane, or to mixtures of alkanes and alkenes such as propane and propene, the composition of the feed gas may be selected in accordance with the conditions for propane.

Typical reaction conditions for the oxidation of propane or isobutane to acrylic acid or methacrylic acid may be utilized in the practice of the present invention. The process may be practiced in a single pass mode (only fresh feed is fed to the reactor) or in a recycle mode (at least a portion of the reactor effluent is returned to the reactor). General conditions for the process of the present invention are as follows: the reaction temperature can vary from 200°C to 700°C, but is usually in the range of from 200°C to 550°C, more preferably 250°C to 480° C, most preferably 300°C to 400°C; the gas space velocity, SV, in the vapor phase reaction is usually within a range of from 100 to 10,000 hr^{-1}, preferably 300 to 6,000 hr^{-1}, more preferably 300 to 2,000 hr^{-1}; the average contact time with the catalyst can be from 0.01 to 10 seconds or more, but is usually in the range of from 0.1 to 10 seconds, preferably from 0.2 to 6 seconds; the pressure in the reaction zone usually ranges from 0 to 75 psig, but is preferably no more than 50 psig. In a single pass mode process, it is preferred that the oxygen be supplied from an oxygen-containing gas such as air. The single pass mode process may also be practiced with oxygen addition. In the practice of the recycle mode process, oxygen gas by itself is the preferred source so as to avoid the build up of inert gases in the reaction zone.

Of course, in the oxidation reaction of the present invention, it is important that the hydrocarbon and oxygen concentrations in the feed gases be maintained at the appropriate levels to minimize or avoid entering a flammable regime within the reaction zone or

especially at the outlet of the reactor zone. Generally, it is preferred that the outlet oxygen levels be low to both minimize after-burning and, particularly, in the recycle mode of operation, to minimize the amount of oxygen in the recycled gaseous effluent stream. In addition, operation of the reaction at a low temperature (below 450°C) is extremely attractive because after-burning becomes less of a problem, which enables the attainment of higher selectivity to the desired products. The catalyst of the present invention operates more efficiently at the lower temperature range set forth above, significantly reducing the formation of acetic acid and carbon oxides, and increasing selectivity to acrylic acid. As a diluting gas to adjust the space velocity and the oxygen partial pressure, an inert gas such as nitrogen, argon or helium may be employed.

When the oxidation reaction of propane, and especially the oxidation reaction of propane and propene, is conducted by the method of the present invention, carbon monoxide, carbon dioxide, acetic acid, etc. may be produced as by-products, in addition to acrylic acid. Further, in the method of the present invention, an unsaturated aldehyde may sometimes be formed depending upon the reaction conditions. For example, when propane is present in the starting material mixture, acrolein may be formed; and when isobutane is present in the starting material mixture, methacrolein may be formed. In such a case, such an unsaturated aldehyde can be converted to the desired unsaturated carboxylic acid by subjecting it again to the vapor phase catalytic oxidation with the doped mixed metal oxide-containing catalyst of the present invention or by subjecting it to a vapor phase catalytic oxidation reaction with a conventional oxidation reaction catalyst for an unsaturated aldehyde.

Turning now in more specific detail to the third aspect of the present invention, the method of the present invention comprises subjecting an alkane, or a mixture of an alkane and an alkene, to a vapor phase catalytic oxidation reaction with ammonia in the presence of a catalyst containing the above mixed metal oxide, to produce an unsaturated nitrile.

In the production of such an unsaturated nitrile, as the starting material alkane, it is preferred to employ a C_{3-8} alkane such as propane, butane, isobutane, pentane, hexane and heptane. However, in view of the industrial application of nitriles to be produced, it is preferred to employ a lower alkane having 3 or 4 carbon atoms, particularly propane and isobutane.

Similarly, as the starting material mixture of alkane and alkene, it is preferred to employ a mixture of C_{3-8} alkane and C_{3-8} alkene such as propane and propene, butane and butene, isobutane and isobutene, pentane and pentene, hexane and hexene, and heptane and

heptene. However, in view of the industrial application of nitriles to be produced, it is more preferred to employ a mixture of a lower alkane having 3 or 4 carbon atoms and a lower alkene having 3 or 4 carbon atoms, particularly propane and propene or isobutane and isobutene. Preferably, in the mixture of alkane and alkene, the alkene is present in an amount of at least 0.5% by weight, more preferably at least 1.0% by weight to 95% by weight, most preferably 3% by weight to 90% by weight.

The purity of the starting material alkane is not particularly limited, and an alkane containing a lower alkane such as methane or ethane, air or carbon dioxide, as impurities, may be used without any particular problem. Further, the starting material alkane may be a mixture of various alkanes. Similarly, the purity of the starting material mixture of alkane and alkene is not particularly limited, and a mixture of alkane and alkene containing a lower alkene such as ethene, a lower alkane such as methane or ethane, air or carbon dioxide, as impurities, may be used without any particular problem. Further, the starting material mixture of alkane and alkene may be a mixture of various alkanes and alkenes.

There is no limitation on the source of the alkene. It may be purchased, per se, or in admixture with an alkane and/or other impurities. Alternatively, it can be obtained as a by-product of alkane oxidation. Similarly, there is no limitation on the source of the alkane. It may be purchased, per se, or in admixture with an alkene and/or other impurities. Moreover, the alkane, regardless of source, and the alkene, regardless of source, may be blended as desired.

The detailed mechanism of the ammoxidation reaction of this aspect of the present invention is not clearly understood. However, the oxidation reaction is conducted by the oxygen atoms present in the above-doped mixed metal oxide or by the molecular oxygen in the feed gas. When molecular oxygen is incorporated in the feed gas, the oxygen may be pure oxygen gas. However, since high purity is not required, it is usually economical to use an oxygen-containing gas such as air.

As the feed gas, it is possible to use a gas mixture comprising an alkane, or a mixture of an alkane and an alkene, ammonia and an oxygen-containing gas. However, a gas mixture comprising an alkane or a mixture of an alkane and an alkene and ammonia, and an oxygen-containing gas may be supplied alternately.

When the gas phase catalytic reaction is conducted using an alkane, or a mixture of an alkane and an alkene, and ammonia substantially free from molecular oxygen, as the feed gas, it is advisable to employ a method wherein a part of the catalyst is periodically withdrawn and

sent to an oxidation regenerator for regeneration, and the regenerated catalyst is returned to the reaction zone. As a method for regenerating the catalyst, a method may be mentioned wherein an oxidizing gas such as oxygen, air or nitrogen monoxide is permitted to flow through the catalyst in the regenerator usually at a temperature of from 300°C to 600°C.

The third aspect of the present invention will be described in further detail with respect to a case where propane is used as the starting material alkane and air is used as the oxygen source. The proportion of air to be supplied for the reaction is important with respect to the selectivity for the resulting acrylonitrile. Namely, high selectivity for acrylonitrile is obtained when air is supplied within a range of at most 25 moles, particularly 1 to 15 moles, per mole of the propane. The proportion of ammonia to be supplied for the reaction is preferably within a range of from 0.2 to 5 moles, particularly from 0.5 to 3 moles, per mole of propane. This reaction may usually be conducted under atmospheric pressure, but may be conducted under a slightly increased pressure or a slightly reduced pressure. With respect to other alkanes such as isobutane, or to mixtures of alkanes and alkenes such as propane and propene, the composition of the feed gas may be selected in accordance with the conditions for propane.

The process of the third aspect of the present invention may be conducted at a temperature of, for example, from 250°C to 480°C. More preferably, the temperature is from 300°C to 400°C. The gas space velocity, SV, in the gas phase reaction is usually within the range of from 100 to 10,000 hr^{-1}, preferably from 300 to 6,000 hr^{-1}, more preferably from 300 to 2,000 hr^{-1}. As a diluent gas, for adjusting the space velocity and the oxygen partial pressure, an inert gas such as nitrogen, argon or helium can be employed. When ammoxidation of propane is conducted by the method of the present invention, in addition to acrylonitrile, carbon monoxide, carbon dioxide, acetonitrile, hydrocyanic acid and acrolein may form as by-products.

Turning now in more specific detail to the fourth aspect of the present invention, as discussed previously, the catalysts or catalyst precursors may be formed alternatively by the use of a deposition technique such as chemical vapor deposition, physical vapor deposition or the like, and then optionally doped in accordance with the above-described doping. Preferably, the ingredients of the catalysts or catalyst precursors are deposited layer by layer, as thin films of the respective individual ingredients onto a suitable support surface. Thereafter, the resulting materials are calcined or otherwise treated.

The mixed metal oxides described in connection with the above first through third preferred aspects of the present invention may be advantageously prepared through the

present deposition techniques. In an alternate highly preferred embodiment, the preferred resulting oxide material is based upon the oxides of Mo-V-Nb-X, where X is at least one element selected from the group consisting of Ta, Ti, Al, Zr, Cr, Mn, Fe, Ru, Co, Rh, Ni, Pt, B, In, Ce, As, Ge, Sn, Li, Na, K, Rb, Cs, Fr, Be, Mg, Ca, Sr, Ba, Hf, Pb, P, Pm, Eu, Gd, Dy, Ho, Er, Tm, Yb, Lu, Au, Ag, Re, Pr, Zn, Ga, Pd, Ir, Nd, Y, Sm, Tb, Cu and Sc. Another preferred resulting oxide material is defined as based upon the oxides of Mo-V-Te-X^1, where X^1 is at least one element selected from the group consisting of Sc, Y, La, Re, Ir, Cu, Ag, Au, Zn, Ga, Si, Ge, As, Pb, S, Se, Sn and Bi.

The resulting catalysts or catalyst precursors are then used in the above described processes for the vapor phase catalytic oxidation of alkanes or a mixture of alkanes and alkenes to their corresponding unsaturated carboxylic acids, or in the production of unsaturated nitriles by subjecting alkanes or a mixture of alkanes and alkenes to vapor phase catalytic oxidation in the presence of ammonia.

As illustrated by the following Examples, the treated catalyst of the present invention exhibits excellent conversion, selectivity and yield characteristics as compared with an untreated catalyst composition. For instance, for each of the reactions of interest, preferably the treated catalyst composition of the present invention exhibits a yield of at least 1.1 times, and more preferably at least 1.5 times the yield, and still more preferably at least 2 times the yield achievable using an untreated catalyst of like composition in a vapor phase catalytic partial oxidation reaction. For each of the reactions of interest, preferably the treated catalyst composition of the present invention exhibits an alkane or alkane/alkene starting material gas conversion of at least 1.1 times, and more preferably at least 1.5 times the conversion, and still more preferably at least 2 times the conversion achievable using an untreated catalyst of like composition. Moreover, for each of the reactions of interest, preferably the treated catalyst composition of the present invention exhibits a selectivity of at least 1.1 times, and more preferably at least 1.5 times the selectivity, and still more preferably at least 2 times the selectivity achievable using an untreated catalyst of like composition.

Another benefit of the present invention is that the employment of sputtering obviates the need for wet chemical or solution treatment techniques for improving catalytic performance. In turn, this avoids additional washing, filtration, drying or calcination steps, which take time and require expensive energy resources. The ability to treat a catalyst with metals instead of their respective salts also provides considerable manufacturing flexibility. Of course, the present invention may be used in combination with wet chemical or solution treatments, with or without metal salts.

Examples

Examples 1 - 5

In a flask containing 390g of water, 46.4g of ammonium heptamolybdate tetrahydrate (Aldrich Chemical Company), 9.2g of ammonium metavanadate(Alfa-Aesar) and 13.9g of telluric acid (Aldrich Chemical Company) were dissolved upon heating to 80°C. After cooling to 20°C, 201.3g of an aqueous solution of niobium oxalate (Reference Metals Company) containing 10.44 mmole/g of niobium was mixed therewith to obtain a solution. The water of this solution was removed via a rotary evaporator at a temperature of 50°C and a pressure of 28mmHg to obtain 73g of a precursor solid. Of the solid precursor, 25 g were calcined in a quartz tube. Specifically, the quartz tube was placed in an oven under an air atmosphere. The oven was heated to 275°C and held there for one hour. A flow of argon (100cc/min) over the precursor material was commenced and the oven was heated to 600°C, where it was then held for two hours. The calcined catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Approximately 0.5g of the granules were packed into a quartz tube reactor for the gas phase oxidation of propane. The oxidation was conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor was analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results (along with residence time and reaction temperature) are shown in Table 1.

Table 1

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
1	3	344	5.0	40.0	2.0
2	3	362	8.0	50.0	4.0
3	3	372	11.0	45.0	5.0
4	3	380	13.0	54.0	7.0
5	3	390	16.0	50.0	8.0

Examples 6 - 10

Approximately six grams of catalyst prepared in Example 1 (fine catalyst powder) was taken in an aluminum weighing pan and put in a sputter coater. A Au-Pd alloy (1:1) sheet was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 20 seconds. The doped catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Approximately 0.5g of the granules were packed into a quartz tube reactor for the gas phase oxidation of propane. The oxidation was conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor was analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results (along with residence time and reaction temperature) are shown in Table 2.

Table 2

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
6	3	326	9.0	78.0	7.0
7	3	344	13.0	77.0	10.0
8	3	355	16.0	75.0	12.0
9	3	369	26.0	63.0	17.0
10	3	376	27.0	61.0	17.0

Examples 11 - 15

Approximately 6 grams of catalyst prepared in Example 1 (fine catalyst powder) was taken in an aluminum weighing pan and put in the sputter coater. A Au-Pd alloy (1:1) sheet was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 40 seconds. The doped catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Approximately 0.5g of the granules were packed into a quartz tube reactor for the gas phase oxidation of propane. The oxidation was conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor was analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results (along with residence time and reaction temperature) are shown in Table 3.

Table 3

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
11	3	327	8.0	62.0	5.0
12	3	349	13.0	62.0	8.0
13	3	356	15.0	67.0	10.0
14	3	371	21.0	62.0	13.0
15	3	383	26.0	56.0	15.0

Examples 16 - 20

Approximately six grams of catalyst prepared in Example 1 (fine catalyst powder) was taken in an aluminum weighing pan and put in the sputter coater. A Au-Pd alloy (1:1) sheet was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 60 seconds. The catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Approximately 0.5g of the granules were packed into a quartz tube reactor for the gas phase oxidation of propane. The oxidation was conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor was analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results (along with residence time and reaction temperature) are shown in Table 4.

Table 4

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
16	3	336	11.0	73.0	8.0
17	3	350	15.0	67.0	10.0
18	3	357	18.0	67.0	12.0
19	3	371	24.0	63.0	15.0
20	3	384	30.0	52.0	16.0

Examples 21 - 25

Approximately six grams of catalyst prepared in Example 1 (fine catalyst powder) was taken in an aluminum weighing pan and put in the sputter coater. A Au-Pd alloy (1:1) sheet was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 120 seconds. The catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Approximately 0.5g of the granules were packed into a quartz tube reactor for the gas phase oxidation of propane. The oxidation was conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor was analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results (along with residence time and reaction temperature) are shown in Table 5.

Table 5

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
21	3	338	11.0	73.0	8.0
22	3	350	15.0	67.0	10.0
23	3	358	19.0	63.0	12.0
24	3	372	24.0	63.0	15.0
25	3	385	30.0	52.0	16.0

Examples 26 - 28

In a flask containing 150g of water, 34.00g of ammonium heptamolybdate tetrahydrate (Aldrich Chemical Company), 6.69g of ammonium metavanadate(Alfa-Aesar) and 10.17g of telluric acid (Aldrich Chemical Company) were dissolved upon heating to 70° C. After cooling to 40°C, 155.93g of an aqueous solution of niobium oxalate (Reference Metals Company) containing 15.28 mmole/g of niobium and 3.76g oxalic acid (Aldrich chemical Company) was mixed therewith to obtain a solution. The water of this solution was removed via a rotary evaporator at a temperature of 50°C and a pressure of 28mmHg to obtain the precursor solid. The solid precursor was calcined in a quartz tube. Specifically, the quartz tube was placed in an oven under an air atmosphere. The oven was heated to 275°C and held there for one hour. A flow of argon (100cc/min) over the precursor material was then commenced and the oven was heated to 600°C and held there for two hours. The calcined catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Of this, 10g of granules were packed into a stainless steel U-tube reactor (with an inside diameter of 1.1 cm) for the gas phase oxidation of propane. The U-tube reactor was placed in a molten salt bath and fed with a mixture of propane, air and steam having a feed ratio of propane/air/steam of 1/10/3 and having a space velocity of 1200 hr^{-1}. The effluent of the reactor was condensed to separate a liquid phase and a gas phase. The gas phase was analyzed by gas chromatography to determine the propane conversion. The liquid phase was

also analyzed by gas chromatography for the yield of acrylic acid. The results (along with residence time and reactor temperature) are shown in Table 6.

Table 6

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
26	3	350	49.0	62.3	30.5
27	3	360	59.8	60.5	36.2
28	3	363	63.2	56.7	35.8

Examples 29-33

Approximately 10 grams of catalyst prepared in Example 26 (fine catalyst powder) was taken in an aluminum weighing pan and put in the sputter coater. Palladium foil was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 60 seconds. The catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Of this, 4.0 g of granules were packed into a stainless steel straight down flow (SDF) tube reactor (inside diameter of 1.1 cm) for the gas phase oxidation of propane. The SDF reactor was placed in a furnace and fed with a mixture of propane, air and steam having a feed ratio of propane/air/steam of 1/10/3 and having a space velocity of 1200 hr^{-1}. The effluent of the reactor was condensed to separate a liquid phase and a gas phase. The gas phase was analyzed by gas chromatography to determine the propane conversion. The liquid phase was also analyzed by gas chromatography for the yield of acrylic acid. The results (along with residence time and reactor temperature) are shown in Table 7.

Table 7

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
29	6	344	71.4	55.2	39.4
30	3	345	58.9	61.8	36.4
31	4.5	344	69.7	55.9	38.9
32	3	347	65.1	58.0	37.8
33	3	350	65.2	59.6	38.8

Examples 34 - 37

Approximately 10 grams of catalyst prepared in Example 26 (fine catalyst powder) was taken in an aluminum weighing pan and put in the sputter coater. A Au-Pd alloy (1:1) sheet was used as the sputtering target and was sputtered in an Ar atmosphere (150 millitorr) at 40 milliamps for a duration of 60 seconds. The catalyst, thus obtained, was pressed in a mold and then broken and sieved to 10 - 20 mesh granules. Of this, 4.0 g of granules were packed into a stainless steel Straight down flow (SDF) tube reactor (inside diameter of 1.1 cm) for the gas phase oxidation of propane. The SDF reactor was placed in a furnace and fed with a mixture of propane, air and steam having a feed ratio of propane/air/steam of 1/10/3 and having a space velocity of 1200 hr^{-1}. The effluent of the reactor was condensed to separate a liquid phase and a gas phase. The gas phase was analyzed by gas chromatography to determine the propane conversion. The liquid phase was also analyzed by gas chromatography for the yield of acrylic acid. The results (along with residence time and reactor temperature) are shown in Table 8.

Table 8

Example	Residence Time (sec)	Temperature (°C)	Propane Conversion (%)	Acrylic Acid Selectivity (%)	Acrylic Acid Yield (%)
34	4.5	350	69.6	53.8	37.4
35	3	353	69.1	58.6	40.5
36	3	346	58.5	62.7	36.7
37	4.5	353	70.1	53.5	37.5

Examples 38 – 39

Physical vapor deposition is performed to sequentially deposit a plurality of different metal films with controlled film thickness. The following materials are deposited in the order listed and with the thicknesses shown in parentheses:

Example 38: Mo (72 nm), then V (19 nm), then Nb (10 nm), then Te (36 nm).

Example 39: Mo (72 nm), then V (19 nm), then Nb (10 nm), then Te (36 nm), then Nb (10 nm).

The mixed metal oxide films are deposited on a Si wafer (7.7 cm x 7.7 cm), which is then sectioned into samples of about one square centimeter. These samples are then calcined and optionally doped thereafter. The samples are then placed in a quartz tube reactor for the gas phase oxidation of propane. The oxidation is conducted with a feed ratio of propane/steam/air of 1/3/96. The effluent from the reactor is analyzed by infrared spectrometry (IR) to determine the propane conversion and the yield of acrylic acid. The results are at least on the order of those of the above Table 1. Improved conversion, yield and selectivity results are achieved by further depositing an Au-Pd alloy on the films before the oxidation reaction.